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Forecasting olive crop yields based on long-term aerobiological data series and bioclimatic conditions for the southern Iberian Peninsula

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Abstract

In the present study, bio-meteorological models for predicting olive-crop production in the southern Iberian Peninsula were developed. These covered a 16-year period: 1994-2009. The forecasting models were constructed using the partial least-squares regression method, taking the annual olive yield as the dependent variable, and both aerobiological and meteorological parameters as the independent variables. Two regression models were built for the prediction of crop production prior to the final harvest at two different times of the year: July and November. The percentage variance explained by the models was between 83% and 93%. Through these forecasting models, the main factors that influence olive-crop yield were identified. Pollen index and accumulated precipitation, especially as rain recorded during the pre-flowering months, were the most important parameters for providing an explanation of fluctuations in fruit production. The temperature recorded during the two months preceding budburst was another important variable, which showed positive effects on the final yield. The July model that provides accurate predictions of fruit production eight months prior to the final harvest is proposed as an optimal model to forecast fruit produced by olive trees in western Mediterranean areas.

Additional key words: forecasting model; fruit production; *Olea europaea* L.; partial least-squares regression; pollen emission.

Introduction

Olive (*Olea europaea* L.) is one of the most extensive crops in the Mediterranean region, and it has social and economic roles that are of paramount importance. Olive fruit and oil are among the oldest and most important products, with the oil representing 90% of the economic benefits. Spain produces 42% of the total olive oil output in the world, as the largest olive-growing area (International Olive Council, 2011). Within Spain, the largest olive-producing area is the province of Jaen (eastern Andalusia). According to Araque *et al.* (2002), the olive groves in Jaen are the most productive in Spain, and they have served as a model in several experiments carried out throughout the Guadalquivir Valley, Spain. There are more than 570,000 ha of olive groves that cover 90% of the agricultural area of Jaen, which make this province in Spain the largest extension of olive groves in the world (Barranco *et al.,* 2008; International Olive Council, 2011). Furthermore, in this intensive monovarietal cultivation, 97% of the olive trees are the 'Picual' cultivar. Thus, the olive groves of Jaen province can be considered as an excellent experimental scenario for the elaboration of forecasting models.

In recent years, the importance of agricultural forecasting has increased, and the quantitative forecasting of yields has become a valuable tool in the support of the producers in the olive sector (Orlandi *et al.,* 2010). An accurate early estimate of crop yield has practical applications in different activities, such as oil transformation efficiency, stock management, marketing strategies, global commercial distribution, and optimization of the human resources necessary for the harvest.

The use of long-term data series has been shown to be a good crop-forecasting technique for numerous species (Miller, 1990; Sharman *et al.,* 1992; De Boissezon, 1995; Palm, 1995; Orlandi *et al.*, 2005a). The close relationships between pollen emission and fruit production have been widely studied, particularly

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in anemophilous crops. Optimal results have been obtained for European hazelnut (*Corylus avellana* L.; Lletjos *et al*., 1993), grape (*Vitis vinifera* L.; Baugnent, 1991; Cunha *et al*., 2003), and olive (*Olea europaea* L.; Fornaciari *et al*., 2002, 2005; Ribeiro *et al*., 2007; Galán *et al*., 2008; García-Mozo *et al*., 2008; Orlandi *et al.,* 2010). A crop-yield model based on pollen emissions of olive was previously developed for the province of Jaen, although no environmental variables were included (Galán *et al*., 2008). However, forecasting models based solely on airborne pollen sampling cannot be complete. Olive trees are influenced by several weather and agronomic conditions during both the pre-flowering period and the time period between flowering and harvest, such as water deficit, temperature extremes and phytopathological problems. These can have negative impact on fruit quantity and quality, and thus increase the interannual variability of the final fruit production (Galán *et al*., 2008; Ribeiro *et al*., 2008; Rapoport *et al*., 2012).

On other hand, from a climate point of view, significant and large warming is expected in the future for the Mediterranean basin. This is based on different greenhouse gas emission scenarios, and decreasing trends in rainfall patterns have been detected (Giorgi & Lionello, 2008; Capra & Pavanelli, 2010; Vergni & Todisco, 2011). However, the effects of climate change on the Mediterranean olive-growing areas might depend on how these changes in temperature and rainfall patterns occur. In this way, a recent study discussed how some typical areas of olive cultivation might be particularly sensitive to projected climate change, and above all, the southern Mediterranean areas, which might become unsuitable for olive cultivation (Moriondo *et al*., 2013). As changes in climate can cause serious imbalances to physiological and biological rhythms of natural and cultivated plant species, models that predict phenological stages can be used to study the responses of plant life-cycle to global warming (Chuine *et al*., 1999; García-Mozo *et al*., 2008; Orlandi *et al*., 2014). In particular, crop modeling can be useful to predict the effect of climatic variability on crop growth, development and yield (Porter & Semenov, 2005; Challinor & Wheeler, 2008).

The aim of the present study was to develop bio-meteorological models for reliable olive-crop forecasting that are based on the relationships among pollen emission and meteorological parameters. Through these models, the main factors that influence olive-crop yield in the southern Iberian Peninsula can be identified, and the response of the fruit production to possible climate change can be discussed.

Material and methods

This study was carried out in the province of Jaen (13,498 km^2), which is located in the southeast of the Iberian Peninsula (Fig. 1). The climate profile is continental Mediterranean, with cold winters and hot, dry summers. The annual average temperature is 15.8°C, and the annual average precipitation is 667 mm.

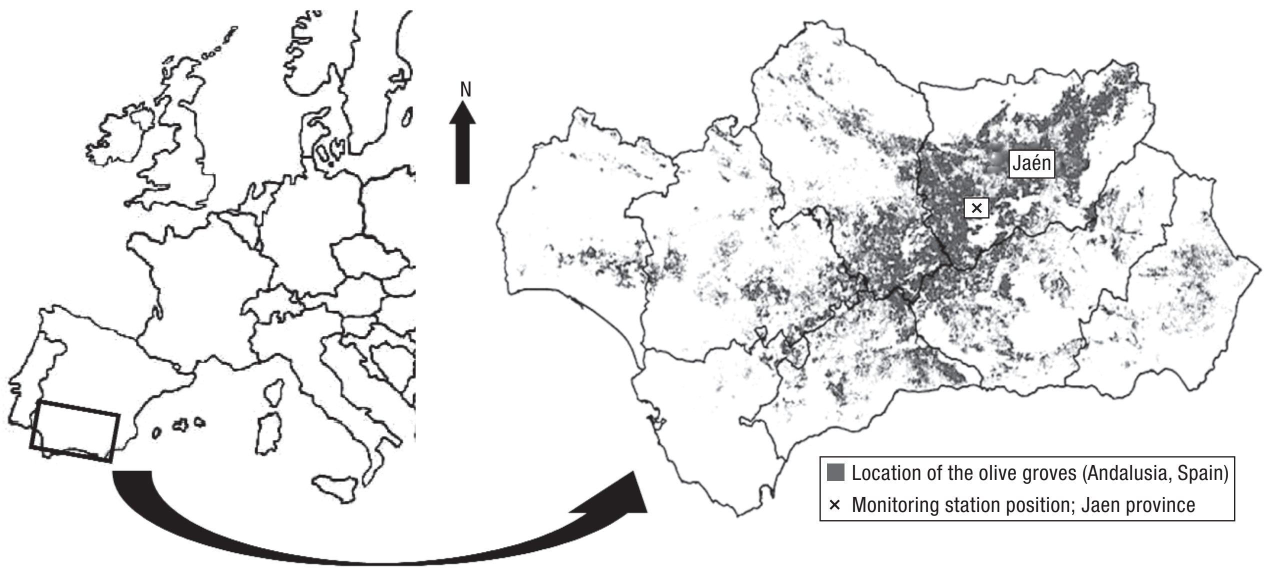

Figure 1. Location of the olive groves in Andalusia (Spain) and the monitoring station in the province of Jaén.

Aerobiological data

The biological parameter considered in this study is the olive pollen captured in the atmosphere during the olive flowering period, using aerobiological monitoring. Pollen emission data for the olive trees were collected continuously over a 16-year period (1994-2009), using Hirst-type volumetric pollen trap (Burkard model) (Hirst, 1952). This trap has a lower fixed part and an upper mobile part that can monitor olive pollen emissions in areas of 2,000 ha, or within a radius of 100 km from the trap position, to study flowering in vegetable species that are characterized by total or partial anemophily (Fornaciari *et al*., 2000; Galán *et al*., 2004). A constant air flow (10 L min^{-1}), that contains the airborne material, passes into the opening of the trap. The airborne particles stick to a drum that revolves at 2 mm h^{-1}. Considering the volume of air that enters the trap, the concentration of particles can be expressed per cubic meter, as hourly, daily or weekly. The data collected were used to calculate the daily pollen concentrations in the air, and subsequently, to construct a complete emission spectrum (Fornaciari *et al*., 2000). The monitoring station was located in the south of the province of Jaen, where the majority of the olive-growing area is concentrated (Fig. 1). This area, completely surrounded by olive groves (37° 48' N, 03° 48' W), is located at an altitude of 568 m a.s.l. The trap was placed 15 m above ground level. The standard data management procedures were used following the recommendations of the Spanish Aerobiology Network (Galán *et al*., 2007).

Three aerobiological variables were calculated: (a) the pollen index, as the sum of the daily pollen concentrations per cubic meter of air during the whole pollen season. The start of the pollen season was defined as the first day on which at least 5 pollen grains m^{-3} were collected, with the subsequent days containing ≥ 5 pollen grains m^{-3}. The end of the season was the last day on which 5 pollen grains m^{-3} were collected, when the subsequent days had concentrations of < 5 pollen grains m^{-3} (modification of the criterion described by Galán *et al*., 2001); (b) the prepeak index, as the sum of the daily pollen counts from the start of the pollen season to the maximum pollen concentration date; *i.e.,* the peak pollination date; and (c) the effective pollination period, as the sum of the daily pollen concentrations of the 4 days preceding the peak pollination date (Orlandi *et al*., 2005b).

Meteorological data

The meteorological variables considered in the present study were: monthly average of maximum and minimum temperatures (°C) and relative humidity (%), monthly accumulated precipitation (mm) and evapotranspiration (mm day^{-1}), summer period (21st of June to 21st of September) accumulated mean temperature (°C) and accumulated precipitation (mm), and accumulated precipitation since the pre-flowering start date (end of March) until the peak pollination day (mm). The mean start date of the pre-flowering period of the olive trees (*i.e.,* the onset of flower bud development) in the province of Jaen was estimated previously from field observations (Aguilera & Ruiz Valenzuela, 2009).

Meteorological data were obtained from the weather station nearest to the monitoring station; *i.e.,* the Spanish Meteorological Agency. The weather station was located at an altitude of 570 m a.s.l. (37°45' N, 03°47' W) and was over 4 km from the trap position.

Statistical analysis

The forecasting models were constructed using the partial least-squares regression technique, taking the annual olive yield as the dependent variable and both the aerobiological and meteorological parameters as the independent variables. Partial least-squares regression is the appropriate statistical technique for the present study given the high number of parameters that can affect the olive tree yield. The modeling was based on linear transformation of the original descriptors to a small number of orthogonal factors (latent variables), to maximize the covariance between the descriptors and the dependent variable. This procedure provides the optimal linear model in terms of the forecasting. In the present study, each latent variable represented a key factor for the olive yield.

The annual olive yield data (tonnes of olive fruit) were provided by the local authorities; *i.e.,* the *Consejería de Agricultura y Pesca, Junta de Andalucía* (Agricultural and Fisheries Department of the Andalusian Regional Government, Jaen Department). Obtaining these data is based on crop production declaration by farmers and oil mills.

First, and according to a previous study carried out in several areas of southern Spain, two models were built for predicting the crop production prior to the final harvest at two different times of the year, to esta-

Table 1. Summary of the partial least-squares regression parameters

Model	Observed production (tonnes)	Predicted production (tonnes)	Determination coefficients		Root mean squared errors	
	Mean ±SD	Mean ± SD	Model R^2	Full cross validation Q^2	R^2	Q^2
1; July	1,929,126 ± 757,762	1,918,623 ± 703,519	0.83	0.76	304,096	371,620
2; November	1,929,126 ± 757,762	1,912,181 ± 754,646	0.93	0.90	195,417	235,385
3; Pebm	1,929,126 ± 757,762	1,910,047 ± 765,654	0.40	0.35	571,351	609,720

Pebm: pollen-emission-based model. SD: standard deviation.

blish the earliest date on which reliable estimations can be obtained (Galán *et al.*, 2008): (i) model 1, or the "July model", which provided predictions of fruit production eight months in advance of the final harvest; and (ii) model 2, or the "November model", which provided predictions of fruit production four months in advance of the final harvest. The same biological variables were used in the calculation of both of these statistical models, although different meteorological parameters were considered. Given that the olive tree is a plant with a 2-year reproductive cycle, the meteorological parameters used were those recorded from December (t-1) to June (t) for the July model, and from December (t-1) to October (t) for the November model. Secondly, a third model following the Pollen-emission-based model (Pebm) previously proposed by Galán *et al*. (2008) for the same province was built. This third model, called model 3, was compared with the bio-meteorological models obtained in the present study.

The models were validated following a full cross-validation method, which is a statistical method for the evaluation and comparison of learning algorithms by dividing the data into two groups: one dataset was used to train the model, and the other was used to validate the model (Refaeilzadeh *et al.,* 2009). According to these authors, the training and validations sets for the cross-validation must cross-over in successive rounds, such that each data point has a chance of being validated against. The advantage of using this validation method is that there is no need to exclude any year for the construction of the statistical models. The STATISTICA 7.0 software (StatSoft Inc., USA) was used for data analysis.

Results

The statistical parameters for the regression models obtained for the prediction of the crop production at different times of the year are given in Table 1. In both bio-meteorological models, the variation explained was high, with determination coefficients (R^2) of 0.83 for model 1 (the July model) and 0.93 for model 2 (the November model). These R^2 values are notably higher than the 0.40 determination coefficient shown by model 3 (the Pebm; Table 1). The coefficients determined for the full cross-validation (Q^2) were generally high, at 0.76 for the July model, and 0.90 for the November model. Again, these Q^2 values are notably higher than the 0.35 coefficient value shown by model 3.

The more important predictive variables involved in the regression output to forecast the fruit production were generally similar in the two bio-meteorological models obtained (Fig. 2). The same biological variable, the pollen index, was included in both of these. This was the aerobiological variable that showed the best relationship with final olive production, showing a high and positive regression coefficient. The pollen index alone explained 40% of the variation of the annual yield, as was shown by the model 3. The meteorological variables related to the accumulated precipitation were particularly relevant in the models. The accumulated precipitation during March and April, which were included in both models, showed high and positive influence on the olive fruit production. Additionally, the accumulated precipitation during the summer period and the accumulated precipitation during October showed positive effects on crop production. These variables were included as predictors in the November model. The other meteorological variables that emerged as important were the average minimum temperature in January, which was included in the July model with a positive regression coefficient, and the average maximum temperature in February, which was included in the two models with positive regression coefficients. Finally, the accumulated evapotranspiration during June was included in the July model.

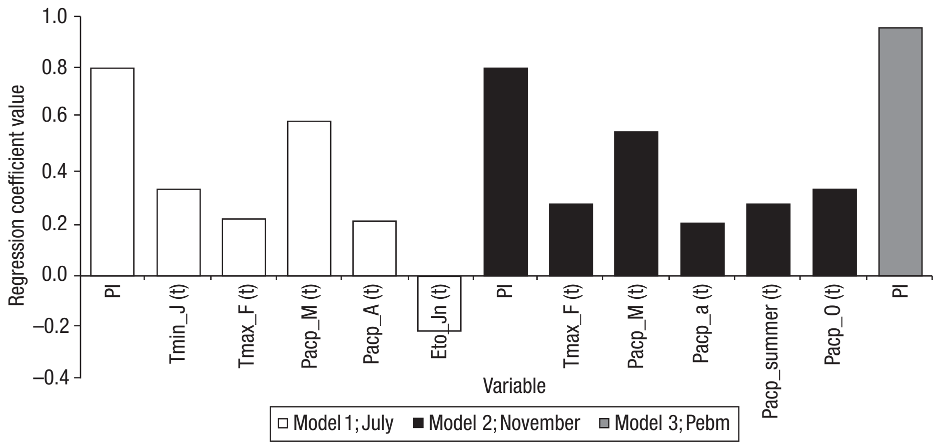

Figure 2. Regression coefficient (R^2) of the variables included in the partial least-squares regression models. PI: pollen index (pollen m^{-3}). Tmin_J: average minimum temperature in January (°C). Tmax_F: average maximum temperature in February (°C). Pacp_M: accumulated precipitation during March (mm). Pacp_A: accumulated precipitation during April (mm). Eto_Jn: accumulated evapotranspiration during June (mm day^{-1}). Pacp_summer: accumulated precipitation during summer (mm day^{-1}). Pacp_O: accumulated precipitation during October (mm). Pebm: pollen-emission-based model.

This variable showed a negative effect on fruit production.

The observed and expected values of the yearly olive yields predicted by the models are reported in Fig. 3. The deviation between observed and predicted production (absolute value) was between 0.13% (2009) and 37% (1999) using the July model (Fig. 3a), and between 0.08% (2000) and 24% (2005) using the November model (Fig. 3b). The deviation between observed and predicted production using the model 3 ranged from 2% (2000) to 95% (1999) (Fig. 3c). The residuals obtained by applying the forecasting models are shown in Fig. 4. These range from –353,000 to +490,000 tonnes using the July model (Fig. 4a), from –268,000 to +387,000 tonnes using the November model (Fig. 4B) and from –805,264 to +855,212 tonnes using the Pebm (Fig. 4C). The mean absolute error was particularly low for the bio-meteorological models, at 13.8% for the July model, and 8.04% for the November model, while a value of 30.7% was obtained for the Pebm.

Discussion

Crop models have proven to be useful tools in the promotion of increased understanding of the mechanisms involved in crop system behaviors. The bio-meteorological forecasting models obtained in the present study were successful generated. In general terms, the yearly crop yields can be accurately predicted by the two models, and the full cross-validation gave acceptable results. These models increase the knowledge of the aerobiological and climatic processes implicated in fruit formation for the olive trees located in the southern Iberian Peninsula.

The incorporation of biological variables in the crop-yield forecasting give the statistical models scientifically acceptable descriptions of the processes involved in the reproductive cycle of the olive. Several studies support the theory that the pre-peak index or the effective pollination period more accurately reflect the flowering period of a particular area, while the pollen recorded in the post-peak period, which corresponds to re-flotation processes or which comes from remote olive-growing areas that have delayed flowering, can introduce redundance in predictive studies on fruit formation (Galán *et al*., 2008; García-Mozo *et al*., 2008; Orlandi *et al*., 2010).

In the present study, the pollen index was the best aerobiological variable to predict the olive harvest in the province of Jaen, and it was included in both of the bio-meteorological forecasting models. There is olive pollen in the atmosphere in Jaen from the second half of April until mid-July, as a result of the chronology in the onset of the olive flowering period, which is delayed and shorter as the crop is distributed at higher altitudes (Aguilera & Ruiz Valenzuela, 2009, 2012). The pollen index, which includes both the pre-peak and post-peak periods, incorporates the full bloom of the different geographical areas located in Jaen, and

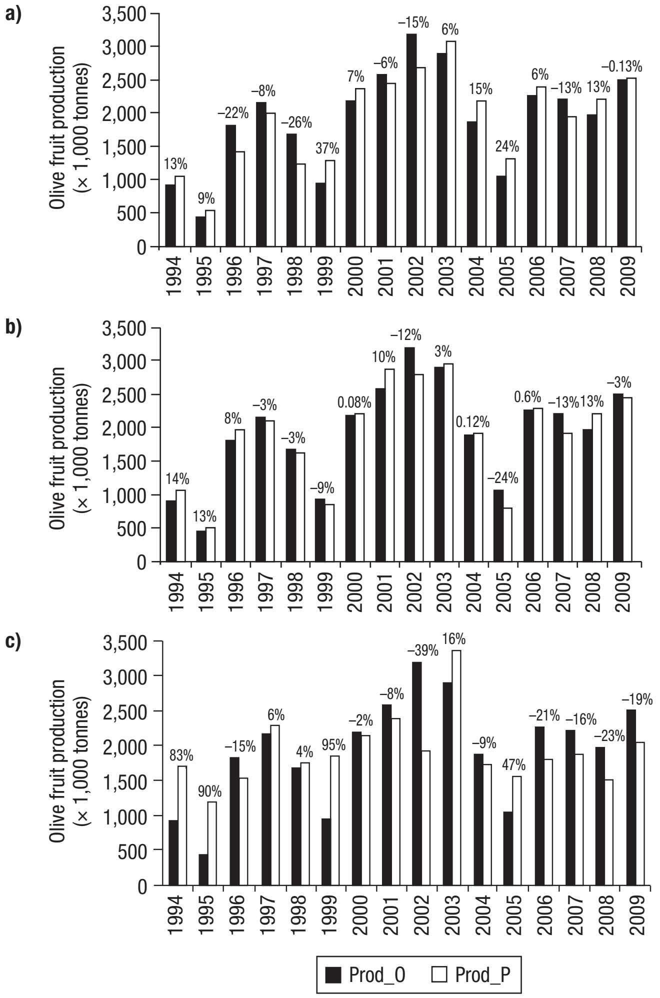

Figure 3. Observed and predicted olive fruit productions. (a) Model 1; July. (b) Model 2; November. (c) Model 3; pollen-emission-based model. Prod_O, observed olive fruit production; Prod_P, predicted olive fruit production. Differences between productions are given above columns, as percentages of observed production (Prod_O).

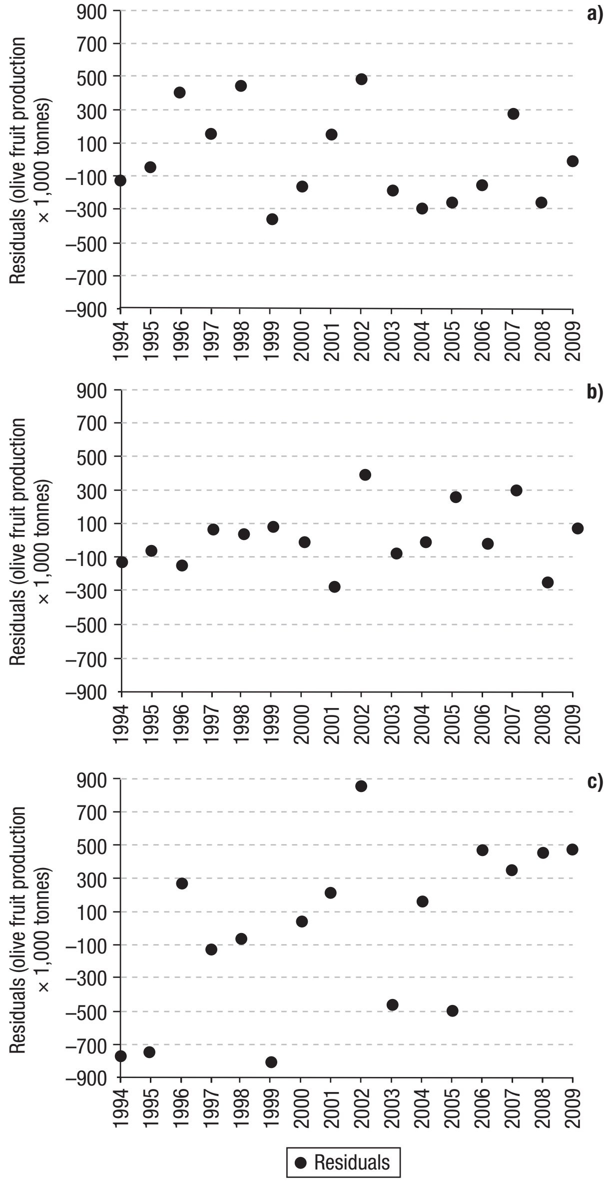

Figure 4. Residuals of the partial least-squares regression models: (a) Model 1; July. (b) Model 2; November. (c) Model 3; pollen-emission-based model.

therefore it can be considered as representative of the whole olive pollen season in the region under study. For this reason, the incorporation of the pollen index into the forecasting models is logical and has proved successful. Although the models were particularly accurate and the aerobiological sampling unit was located at a middle altitude and recorded the pollen of different altitudinal areas, could be convenient increasing number of samplers over large production areas, as has been advocated by other authors (Candau *et al.*, 1998; Ribeiro *et al.*, 2007).

The advantages of incorporating aerobiological variables into olive-forecasting models are numerous. On the one hand, the pollen data represent a synthesis of the whole flowering period in a regional olive-growing area, and they are thus an interesting objective parameter to be used as a variable in forecasting the coming harvest. On the other hand, the conditions during the months before flowering, such as water deficit, or plague or crop management techniques, are reflected in the annual numbers of flowers and amount of pollen produced by olive trees (Ribeiro *et al.*, 2008; Orlandi *et al.*, 2010). Consequently, the pollen index can be used to reflect these variations, to incorporate them indirectly into crop-forecasting models. In addition, the potential of an aeropalynological variable is also because as well as expressing the number of male gametes that are potentially useful for reproduction, the airborne pollen count provides indirect information on the number of available flowers, and consequently of ovaries that will become fruit (Fornaciari *et al*., 2005; Reale *et al*., 2006; Galán *et al*., 2008; Orlandi *et al*., 2010). Nevertheless, the productive capacity of each variety, the percentage of staminiferous flowers, and the ovary abortion, are factors that should be taken into account in future studies (Rovira & Tous, 2005; Serrano *et al*., 2008).

The relationships between the yield and the weather-related conditions have been reported in similar studies carried out in other climate zones (González-Minero *et al*., 1998; Fornaciari *et al*., 2005; Ribeiro *et al*., 2007; Galán *et al*., 2008; Orlandi *et al*., 2010). The bio-meteorological models obtained in the present study represent a clear improvement to the Pebm developed by Galán *et al*. (2008). The incorporation of meteorological variables into the Pebm allowed a greater percentage of the dependent variable variance to be explained, and obtained more accurate crop-yield predictions. The data from the present study confirm that variables such as the cumulative precipitation and the maximum and minimum temperatures during the pre-flowering and post-flowering months are of particular importance in crop production for the southern olive-growing areas.

The precipitation was the most important meteorological factor to provide an explanation for the existing fluctuations in fruit production. The rain recorded during the pre-flowering months when the development of the floral buds takes places has a powerful positive effect on the final crop production of olive trees in the southern Iberian Peninsula. According to Rallo (1994), water stress during the months preceding flowering reduces the number of flowers on olive trees. This might result in both a lower pollen release and a reduced availability of ovaries, and thus potentially of fruit. The same occurs for the summer and autumn rainfalls, which showed favourable effects on the final amount of fruit. According to Lavee (1994), both the development and accumulation of pulp in the fruit is reduced if there is limited rainfall in the months prior to the harvest, which justified the inclusion of this variable in the forecasting models. Several studies on olive harvest prediction made in central and southern Spain (Candau *et al*., 1998; Galán *et al*., 2008; García-Mozo *et al*., 2008; Oteros *et al*., 2012) and other countries, such as Italy (Orlandi *et al*., 2010) and Portugal (Ribeiro *et al*., 2008), are in agreement with this. These studies have highlighted the particular importance of the rainfall during flowering and fruit ripening in Mediterranean climate areas, where there are frequent drought periods (Capra & Pavanelli, 2010; Vergni & Todisco, 2011).

Temperature is another important factor that affects crop production. The temperature is closely related to the biological reproductive cycle of the olive tree, especially within the flowering period (Bonofiglio *et al.*, 2008; Galán *et al*., 2008; Aguilera & Ruiz Valenzuela, 2009; Orlandi *et al*., 2010). High temperatures during the two months preceding budburst have a positive effect on the final fruit production. According to Aguilera *et al*. (2013), the onset of the heat accumulation period usually occurs in the first two weeks of February, and a certain number of days are required to completely satisfy the olive tree biothermic requirements. The relationship between accumulation of temperature and future development of flowers and fruit might explain the inclusion of this variable in the forecasting models. The temperatures recorded during the spring were relevant for the interpretation of the olive production variability in central and southern Italy (Orlandi *et al*., 2010). Moreover, models based on the radiation-use efficiency have been developed, with optimal results, as this index is an interesting parameter that can be used in future studies (Villalobos *et al*., 2006).

Summer evapotranspiration is another important variable that has an influence on crop yield. An increase in evapotranspiration during the dry period, when the water need is at its maximum, can significantly reduce the quantity, and also the quality, of the olive tree fruit (Ribeiro *et al*., 2008; Oteros *et al*., 2013).

Notable tendencies towards increased temperatures and evapotranspiration, together with patterns of lower rainfall, have been detected in the Mediterranean basin (Giorgi & Lionello, 2008; Vergni & Todisco, 2011). Under the context of climate change, the fundamental vegetative and reproductive phases of numerous plant species, such as the olive tree, might have serious problems in their adaptation to the new scenarios (Moriondo *et al*., 2013; Orlandi *et al*., 2014). The processes of pollination, fruit setting, and fruit maturation might be negatively affected, which are aspects to highlight, given the socio-economical importance of olive groves and their products for countries in the Mediterranean region.

According to the criteria established by Sinclair & Seligman (2000) for publishing studies on crop modelling, the heuristic merit of a model is based on several factors: principally, the originality, scientific soundness, and contribution to the science of harvest systems. Under these criteria, the July model can be proposed as an optimal model for forecasting the fruit produced by olive groves in the southern Iberian Peninsula. Previously, crop models developed in the region of study have not related the meteorological parameters to pollen emission. The July model is based on the relationships between the meteorological parameters related to the pre-flowering months and the pollen emission over the whole flowering season, and this provides early and accurate olive-crop forecasting. Although the incorporation of parameters related to the summer season and the months just before the harvest (the November forecast model) increases the degree of explanation of the model by 10%, the July model provides farmers and regional agricultural institutions with information that is of great value for use in harvesting and post-harvesting management and economic planning strategies, such as in the organization of harvesting fields and the global commercial distribution.

Together with similar experience developed in southern Spain (Galán *et al*., 2008), the approach shown in the present study demonstrates the usefulness of yield-forecasting models in western Mediterranean olive-growing areas. Considering that the bio-meteorological models presented in the present study include variables that are closely related to the reproductive stages of the life-cycle of the olive tree, this can be applied to other potentially new situations, and with further work, this should be extendable to other geographical areas.

The bio-meteorological models presented in this study increase the knowledge of the aerobiological and climatic processes that are implicated in fruit formation for olive trees in the southern Iberian Peninsula. In addition, these models represent a notable improvement over previous pollen-emission-based models. Together, the pollen index and the accumulated precipitation, including in particular the rain recorded during the pre-flowering months, are the most important parameters for an explanation of the present fluctuations in fruit production. The July model, which provides accurate predictions of fruit production eight months in advance of the final harvest, is proposed as the most useful for forecasting the fruit production of olive trees in the southern Iberian Peninsula. Moreover, and from a practical point of view, this bio-meteorological model provides useful information to institutions related to the olive-oil sector.

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